

Implementation of a three Phase Inverter with a Front End Diode Rectifier Using Average Model

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Abstract— As technology grows every day, the study of power systems has shifted its direction to power electronics to produce the most efficient energy conversion. Power electronics is the study of processing and controlling the flow of electric energy by supplying voltages and currents in a form that is suited for user loads. A power electronic system is any technical system which is an assembly of components such as AC to DC converters (rectifiers) and DC to AC converters (inverters), that are connected together to form a functioning machine or an operational procedure. The paper presents the implementation of a three phase inverter with a front end diode rectifier. The components are modeled separately using the state space average method.

Keywords— Average Model, Front end diode rectifier and Three phase inverter.

I. INTRODUCTION

Today, power electronics is a rapidly expanding field in electrical engineering and a scope of the technology covers a wide spectrum of electronic converters. Different kinds of power supplies are used everywhere in normal daily routines in both at home, office work or in an industrial environment. This is due to the progress in electronic components and equipment development that has been achieved in the last few decades. A power electronic system assembles rectifiers that convert ac to dc with the adjustment of voltage and current and inverters which produce ac of controllable magnitude and frequency [1].

In the case of a polyphase rectifier, the phase-shifted pulses overlap each other which produce a smoother dc output than that made by a single-phase ac rectifier [2]. The modeling of single phase, three phase rectifiers and suitable controller design for the modeled rectifier circuit is presented in [3]. In [4] the authors have presented a comparative study on the average model of diode rectifier with the model developed by modified nodal analysis method. For the analysis and controller design purpose in inverters, the average modeling method is found to be an effective method [5] – [7]. The modified nodal analysis method and the state space average method in the

modeling of a three phase inverter is discussed in [8]. Conventional switching models and state-space averaging methods which take dead-time effects into consideration have been applied successfully in the inverters [9], [10]. This paper presents the implementation of a three phase inverter using a front diode rectifier. The section II gives the average model of a three phase diode bridge rectifier. The section III gives the average model of a three phase inverter. The section IV explains the implementation of the three phase inverter with a front end diode rectifier and the section V discusses the results and simulations.

II. AVERAGE MODEL OF A THREE PHASE DIODE RECTIFIER

In order to make prime decisions in the design procedures, power electronic modeling methods are widely used. The modeled circuit helps to determine the performance of the circuit along with the component values as well. State space average modeling method is a common technique that is utilized to obtain models of power electronic circuits, for ac and dc power conversions. The main advantage of this particular method is that the accuracy can be increased and ripple free waveforms can be obtained.

A simplified three phase diode bridge rectifier is shown in the Fig. 1. The circuit consists of three ac input sources (V_A , V_B and V_C), input source reactor (L_s), diodes (D_1 to D_6), output inductance (L_{out}), output filter capacitance (C) and resistance (R) which represents the load on the rectifier [11].

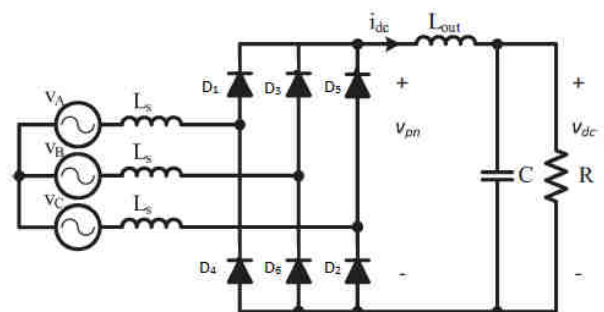


Fig. 1: Simplified circuit model of a three phase diode bridge rectifier

Utilizing the general state space averaging method, the switching functions s_a , s_b and s_c for a three phase diode bridge rectifier can be expressed by a Fourier series using the first harmonic terms of the series as shown in the equation (1).

$$s_{abc} = \frac{2 * \sqrt{3}}{\pi} \left[\sin \omega t \quad \sin \left(\omega t - \frac{2\pi}{3} \right) \quad \sin \left(\omega t + \frac{2\pi}{3} \right) \right]^T \quad (1)$$

The average dc output voltage V_{pn} can be expressed as the equation (2).

$$V_{pn} = s_{abc}^T * v_{abc} = \left(L_{out} * \frac{di_{dc}}{dt} \right) + v_{dc} \quad (2)$$

Also, the dc current equation can be obtained as shown in equation (3).

$$i_{dc} = C \frac{dv_{dc}}{dt} + \frac{v_{dc}}{R} \quad (3)$$

From the equation (2), the left hand side of the equation can be expanded as:

$$\begin{aligned} s_{abc}^T * v_{abc} &= lhs \\ &= \frac{2 * \sqrt{3}}{\pi} \\ &\quad * [(s_a * v_a) + (s_b * v_b) \\ &\quad + (s_c * v_c)] \end{aligned} \quad (4)$$

Now, the right hand side of the equation (2) can be solved using the Transient simulation method. In this method, the differential current equation can be converted to its equivalent Forward Euler form and solved to obtain the value for the $(n+1)^{th}$ value of the dc current.

$$lhs = \left(L_{out} * \frac{i_{dc}^{n+1} - i_{dc}^n}{h} \right) + v_{dc} \quad (5)$$

From the equation (5), the $(n+1)^{th}$ value of the dc current can be calculated as:

$$i_{dc}^{n+1} = \left[\frac{h}{L_{out}} * (lhs - (i_{dc} * R)) \right] + i_{dc} \quad (6)$$

where, 'h' is the delta constant value or the time step.

Similarly, from the equation (3), the differential voltage equation can be converted to its equivalent Forward Euler form and solved to obtain the value for the $(n+1)^{th}$ value of the dc voltage.

$$i_{dc} = C * \left(\frac{v_{dc}^{n+1} - v_{dc}^n}{h} \right) + \frac{v_{dc}}{R} \quad (7)$$

Thus, from the equation (7), the $(n+1)^{th}$ value of the dc voltage can be calculated as:

$$v_{dc}^{n+1} = \left[\frac{h}{C} * (i_{dc}^{n+1} - (v_{dc}/R)) \right] + v_{dc} \quad (8)$$

The modeling equation for a three phase diode bridge rectifier is obtained using the average state space model and the transient simulation techniques. The main modeling equations are equation (4), (6) and (8).

III. AVERAGE MODEL OF A THREE PHASE INVERTER

In the study of inverters and their dynamic performance, various switching models are obtained based on the switching conditions, as in the Modified Nodal Analysis method explained earlier in the chapter, which is feasible for a single inverter or a small scale inverter system. Therefore, in case of large scale inverter systems, switching models becomes complicated. Hence, a state space averaging method is formulated which is effective for the analysis and controller design purpose in inverters. However, it is yet to give guaranteed high accuracy performance.

A generalized state space averaging model is considered which enhances the fundamental voltage and current calculation with desired accuracy and precision. At the same time, this method enables the steady state as well as transient analysis processes [12]. The circuit diagram of a 3 phase 3 wire Voltage source inverter is as shown in the Fig. 2.

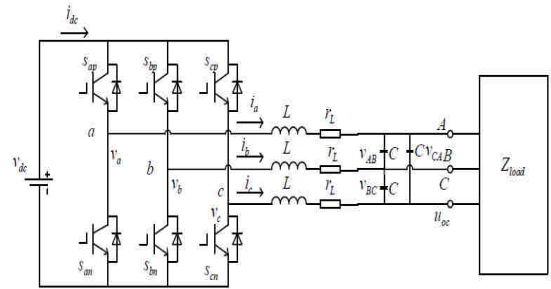


Fig. 2: Circuit diagram of a three phase three wire voltage source inverter

In the Fig. 2, assuming that the loads are 3 phase symmetrical resistive loads in delta connection, whose value are R, we obtain the equations from (9) to (14).

$$v_{ab} = v_a - v_b = L \frac{d(i_a - i_b)}{dt} + r_L(i_a - i_b) + V_{AB} \quad (9)$$

$$v_{bc} = v_b - v_c = L \frac{d(i_b - i_c)}{dt} + r_L(i_b - i_c) + V_{BC} \quad (10)$$

$$v_{ca} = v_c - v_a = L \frac{d(i_c - i_a)}{dt} + r_L(i_c - i_a) + V_{CA} \quad (11)$$

$$i_{ab} = C \frac{dV_{AB}}{dt} + \frac{1}{R} V_{AB} \quad (12)$$

$$i_{bc} = C \frac{dV_{BC}}{dt} + \frac{1}{R} V_{BC} \quad (13)$$

$$i_{ca} = C \frac{dV_{CA}}{dt} + \frac{1}{R} V_{CA} \quad (14)$$

where, i_{ab} , i_{bc} , i_{ca} are virtual line currents which can be calculated as mentioned in the equations from (15) to (20).

$$i_a = i_{ab} - i_{ca} \quad (15)$$

$$i_b = i_{bc} - i_{ab} \quad (16)$$

$$i_c = i_{ca} - i_{bc} \quad (17)$$

$$i_{ab} = \frac{1}{3}(i_a - i_b) \quad (18)$$

$$i_{bc} = \frac{1}{3}(i_b - i_c) \quad (19)$$

$$i_{ca} = \frac{1}{3}(i_c - i_a) \quad (20)$$

Similar to the equation (2) in the modeling of three phase diode bridge rectifier by the average model, it can be written that:

$$v_{ab} = v_a - v_b = (s_a - s_b) \cdot V_{dc} \quad (21)$$

$$v_{bc} = v_b - v_c = (s_b - s_c) \cdot V_{dc} \quad (22)$$

$$v_{ca} = v_c - v_a = (s_c - s_a) \cdot V_{dc} \quad (23)$$

Thus, the conventional state equations of three phase inverter can easily be constructed.

$$\frac{di_{ab}}{dt} = -\frac{r_L}{L} i_{ab} - \frac{1}{3L} V_{AB} + \frac{1}{3L} v_{ab} \quad (24)$$

$$\frac{di_{bc}}{dt} = -\frac{r_L}{L} i_{bc} - \frac{1}{3L} V_{BC} + \frac{1}{3L} v_{bc} \quad (25)$$

$$\frac{di_{ca}}{dt} = -\frac{r_L}{L} i_{ca} - \frac{1}{3L} V_{CA} + \frac{1}{3L} v_{ca} \quad (26)$$

$$\frac{dV_{AB}}{dt} = -\frac{1}{RC} V_{AB} + \frac{1}{C} i_{ab} \quad (27)$$

$$\frac{dV_{BC}}{dt} = -\frac{1}{RC} V_{BC} + \frac{1}{C} i_{bc} \quad (28)$$

$$\frac{dV_{CA}}{dt} = -\frac{1}{RC} V_{CA} + \frac{1}{C} i_{ca} \quad (29)$$

The differential voltage and current equations can be converted to its equivalent Forward Euler form and substituting the equations (21) to (23) in the Forward Euler equations we obtain the value for the (n+1)th value of the corresponding ac voltage and ac current.

$$i_{ab}^{n+1} = h * \left[-\frac{r_L}{L} i_{ab} - \frac{1}{3L} V_{AB} + \frac{1}{3L} (s_a - s_b) \cdot V_{dc} \right] + i_{ab} \quad (30)$$

$$i_{bc}^{n+1} = h * \left[-\frac{r_L}{L} i_{bc} - \frac{1}{3L} V_{BC} + \frac{1}{3L} (s_b - s_c) \cdot V_{dc} \right] + i_{bc} \quad (31)$$

$$i_{ca}^{n+1} = h * \left[-\frac{r_L}{L} i_{ca} - \frac{1}{3L} V_{CA} + \frac{1}{3L} (s_c - s_a) \cdot V_{dc} \right] + i_{ca} \quad (32)$$

$$V_{AB}^{n+1} = \frac{h}{C} i_{ab} + V_{AB} \quad (33)$$

$$V_{BC}^{n+1} = \frac{h}{C} i_{bc} + V_{BC} \quad (34)$$

$$V_{CA}^{n+1} = \frac{h}{C} i_{ca} + V_{CA} \quad (35)$$

The switching function is given by:

$$s_k = \frac{m}{2} \cos(\omega t - \phi_k) + \frac{1}{2} \quad (36)$$

where k = a, b, c ; m is the modulation ratio taken as 0.5

$\phi_a = \phi_0, \phi_b = \phi_0 + \frac{2\pi}{3}, \phi_c = \phi_0 - \frac{2\pi}{3}$; where ϕ_0 is the initial phase angle.

IV. IMPLEMENTATION

The block diagram for the implementation of a three phase inverter with a front end diode rectifier is as shown in the Fig. 3.

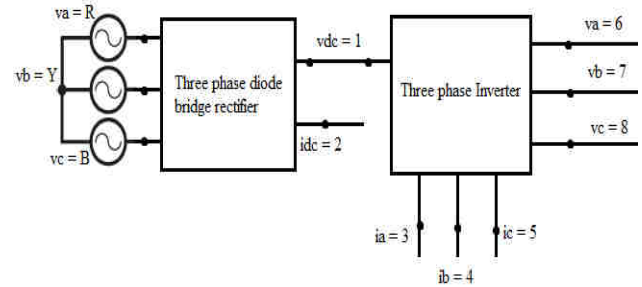


Fig. 3: Block diagram of three phase inverter with a front end diode rectifier

In the block diagram, the three phase diode rectifier is fed by a three phase ac supply R, Y and B. The diode rectifier converts the ac supply to dc values. The nodes 1 and 2 at the output of the rectifier, represents the dc voltage and dc current values respectively. The three phase inverter is used to convert the dc values to ac values. Therefore, the output dc voltage value of the diode rectifier is given as input to the three phase inverter. The ac voltage and current values are obtained at the output side of the three phase inverter. The nodes 3, 4 and 5 represent the output ac phase currents and the nodes 6, 7 and 8 represent the output ac phase voltage values of the three phase inverter fed by a front end diode rectifier.

V. RESULTS AND DISCUSSIONS

The waveforms for the implementation of a three phase inverter with a front end diode rectifier are obtained. The graphs include the three phase supply input, the diode rectifier output and the output voltage and current values of the three phase inverter. The parameter specifications for the average model of three phase diode bridge rectifier are as shown in the Table 1.

Table 1: Parameters for simulation of diode rectifier in average model

| SYMBOL | PARAMETERS | VALUE | UNIT |
|-----------|-----------------------|-------|----------|
| V_{abc} | Input Voltage | 415 | V |
| f | Fundamental frequency | 50 | Hz |
| L | Filtering Inductor | 0.05 | H |
| C | Filter Capacitor | 0.05 | F |
| R | Load Resistance | 2 | Ω |
| h | Time step | 100 | μs |

The Fig. 4 shows the three phase input supply voltage (415 V, 50 Hz) given to the diode rectifier.

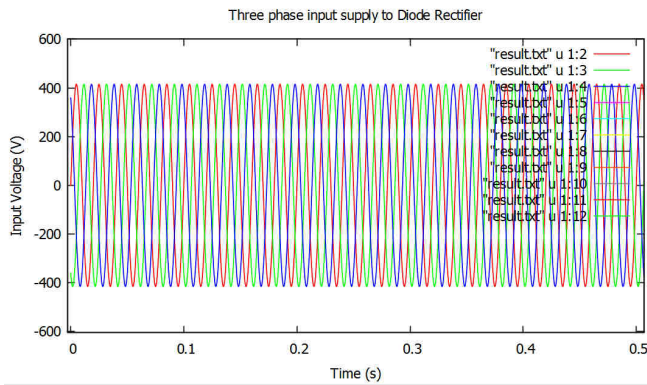


Fig. 4: Three phase supply to the Diode rectifier (415V, 50Hz) (X axis: 1 unit = 0.1s and Y axis: 1 unit = 200V)

The Fig. 5 shows the output dc voltage and current values of the diode rectifier obtained at the nodes 1 and 2 respectively, with the specified modeling parameter specifications.

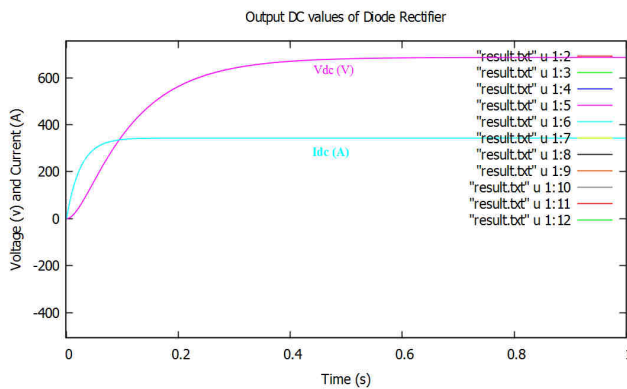


Fig. 5: Output dc voltage and dc current of a 3 phase rectifier, $V_{dc} = 687$ V and $I_{dc} = 343$ A (X axis: 1 unit = 0.2s and Yaxis: 1 unit = 200 units of voltage and current)

The parameter specifications for the average model of three phase inverter are as shown in the Table 2.

Table 2: Parameters for simulation of inverter in average method

| SYMBOL | PARAMETERS | VALUE | UNIT |
|----------|---|-------|----------|
| V_{dc} | Input Voltage (output of the diode rectifier) | 687 | V |
| m | Modulation Ratio | 0.6 | - |
| f | Fundamental frequency | 50 | Hz |
| ϕ_0 | Initial phase angle | 0 | rad/s |
| L | Filtering Inductor | 1.0 | mH |
| r_L | ESR of filtering inductor | 1.245 | Ω |
| C | Filter Capacitor | 1.0 | mF |
| R | Load Resistance | 10 | Ω |
| h | Time step | 100 | μs |

The simulation waveform for phase currents at the output of the inverter is as shown in the Fig. 6. The figure shows

the ac phase currents with a magnitude of 143 A at the nodes 3, 4 and 5 (as in Fig. 3).

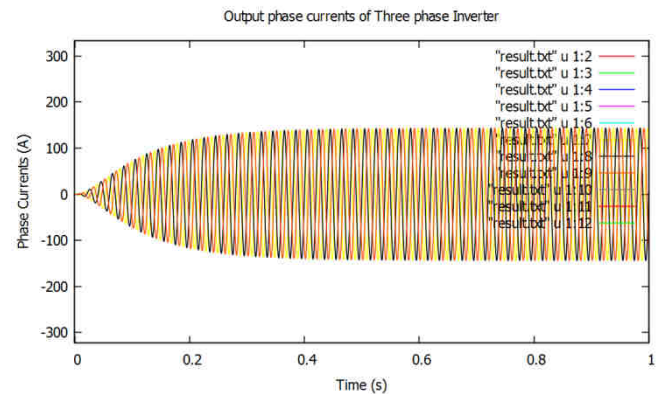


Fig. 6: Output phase current waveform with a magnitude 143 A (X axis: 1 unit = 0.2s and Y axis: 1 unit = 10 A)

The simulation waveform for phase voltages at the output of the inverter is as shown in the Fig. 7. The figure shows the ac phase voltages with a magnitude of ($2V_{dc}/3 = 458$ V) for the given input dc of 687 V at the nodes 6, 7 and 8 (as in Fig. 3).

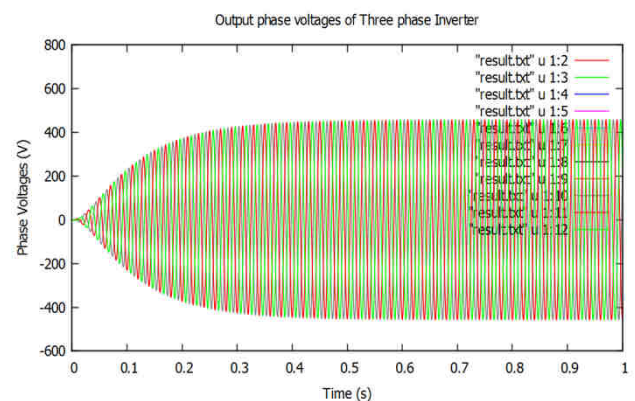


Fig. 7: Output phase voltage waveform with a magnitude 458 V for the dc input of 687 V (X axis: 1 unit = 0.1s and Y axis: 1 unit = 200 V)

VI. CONCLUSION

The paper presents the implementation of a three phase inverter with a front end diode rectifier. The modeling of the three phase diode bridge rectifier and the three phase inverter are done using the generalized state space average method. The three phase inverter is fed from the output dc values of the diode rectifier. The output waveforms of the average model of the diode bridge rectifier and the inverter are obtained. The main advantage of the average model of three phase diode rectifier and three phase inverter is that it gives continuous and ripple free waveforms.

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